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Knowledge representation framework for interactive capture and management of reflection process in product concepts development

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ABSTRACT

A design process can be characterized by reflection-in-action; that is, the process consists of a series of problem solving activities and each is embodied with a problem and a solution. In this process, a designer represents a hypothetical concept on each design alternative, deploys and verifies the concept from multiple viewpoints considering other alternatives, and modifies it. An advanced integrated design environment should be based on a representation framework that embodies this process of reflection in concept development, which usually remains in the realm of the designer's tacit knowledge. This paper proposes a knowledge representation framework for an integrated design environment, named DRIFT (Design Representation Integration Framework of Three layers), which interactively captures and manages reflection processes of generating and verifying design concepts. The core of DRIFT is a three-layered design process model of actions, operations, and argumentation. This model integrates various design tools and captures performed design activities. The action level captures the sequence of design operations. The model operation level captures the transition of design states, recording a design snapshot over design tools, which are integrated through ontology-based representation of design concepts. The argumentation level captures the process of defining problems and corresponding alternative solutions. Integration of three levels with a template of design operation extracted from Design-For-X approaches enables a proposed system to interactively and efficiently capture and manage the process of design concept development through operations over design tools. A design operation template works to limit the number of links between the three levels remaining easy to manage its semantics. This paper also demonstrates a prototype implementation of DRIFT and its application to conceptual design of a small mechatronic system with a system modeling method. The paper concludes with a discussion of some future issues.

1. Introduction

Engineering design is performed to create a novel product, service, or result that has never been done before with a particular set of features. While the design process contains routines or regularized works, it also contains creative activities by nature. Any design problem is somewhat open-ended because of these creative components. Neither a design requirement nor the path to a design solution is necessarily definitive. When the open-endedness is focused, the design process can be characterized by reflection-in-action [1–3]; that is, the process consists of a series of activities simultaneously developing both a problem and a solution, in which a designer represents the hypothetical concept on a design alternative, deploys and verifies the concept from multiple viewpoints considering other alternatives, and modifies it. An advanced integrated design environment should have a representation framework for process of a designer's reflection, which usually remains in the realm of the designer's tacit knowledge.

This paper proposes a new knowledge representation framework called DRIFT (Design Representation Integrated Framework of Three layers) that forms the basis of an advanced integrated design process management environment. Several viewpoints on modeling the design process have been presented in prior work, such as "design as decision making [4]", "design as analysis [5]" and "design as optimization [6]." The present work describes a framework that accepts the assumption that a design activity can be modeled as an operation on a design concept representation, that is, design operation [7]. In order to represent the process of reflection in generation and verification of design concepts and to facilitate dynamic change of these concepts, this research proposes that such an operation is driven by a process of argumentation consisting of the following steps: problem definition, generation of alternative design concepts, and verification of these different concepts considering other alternatives. The features of the framework are summarized as follows:

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1. All design operations during design are recorded in a process model as byproducts of design activities.
2. A three-layered design process model of action, model operation and argumentation is introduced for implementing the functionality noted in item 1 based on interaction between the system and a user.
3. Patterns and templates of design operations, each of which is associated with a unit operation for generating design concepts on an alternative solution to a given design problem, are defined in order to deploy the contents of item 1 into the three-layered model.
4. An ontology-based representation is introduced for managing the diverse content generated by the design operations in an integrated manner.

This research focuses on conceptual design phases utilizing a design method, so called, Design for X (DFX) [8] methodologies for demonstrating the feasibility of the proposed framework. This paper formalizes an ontology and design operation templates by extracting typical representation patterns and typical operation patterns from some DFX methodologies. The argumentation process is represented in the form of a graphical Issue-Based Information System (gIBIS) [9]. Dynamic changes to alternative design concepts are implemented using a justification-based truth maintenance system [10].

This paper consists of eight sections. Section 2 discusses the structure of reflection process in which hypothetical concepts of design alternatives are generated and verified, and addresses the issues of representing these alternatives in an integrated design environment. Features of the proposed system are clarified through comparison with related works. Section 3 gives an overview of the knowledge representation framework proposed in this research. Section 4 explains the contents of the framework. Section 5 presents an example of how the knowledge representation framework may be implemented. Section 6 describes the implementation of a design environment prototype, and demonstrates its application to conceptual design of a small mechatronic system with a system modeling method. Section 7 discusses the outcomes of this research and the open issues that remain. Section 8 concludes this paper.

2. Structure of design process and representation issues

2.1. Design concept

First, this subsection clarifies the definition of design concept. While many studies have been undertaken in the domain of design research to understand and support concept generation, prior authors have applied different meanings to the term. This research classifies these prior definitions into two groups, based on the necessity of knowledge representation. In the first group, authors have defined "design concept" as *an idea of a design solution*; in the second, authors take "design concept" to mean *a designer'sperception or knowledge about an entity*, *function*, *or attribute* that may be used to represent characteristics of the design solution.

The first definition has been mainly used by researchers of creativity and design methodologies [11] that do not necessary require a knowledge representation framework. It is commonly asserted that the number of design concepts gradually decreases and converges as design process continues. Cross [12] characterized the overall design process as being convergent, but maintained that it also contains deliberate divergence for the purpose of widening the search for new ideas. After reaching its peak, the size of the search space of design concepts gradually decrease as the design process continues. The second definition is mainly used by researchers of design theory, knowledge modeling and artificial intelligence who are mainly interested in a knowledge representation for intelligent computational tools supporting design activity. Yoshikawa's general design theory (GDT) [13] is a pioneering work for this approach. The GDT approach introduces two kinds of concepts, the entity concept and the abstract concept. Abstract concepts are associated with the classification of entity concepts according to their meaning or attribute value. Function and physical attributes are examples of abstract concepts. A design solution is represented as a combination of abstract concepts. The number of concepts gradually increases as the design process continues in contrast to the case of the first definition of concept. For the remainder of this paper, we use the design concept of the second definition.

2.2. Reflection process in design concept development

Design is a process of reflection whereby a designer stepwise develops a design concept [1–3]. In other words, a designer handles both a problem and a solution as a hypothetical design concept. He/she uses or often creates the knowledge required for generation and verification of the design concept. The results of verification also comprise hypothetical design concepts, since it is not possible to completely know the usage condition of the finished product, and the verification must be carried out under a limited range of conditions at a specific stage of the design process. By extension, the choice of knowledge or information used in the design process is also a hypothetical design concept. The process of hypothesis-verification is a so-called "non-monotonic" reasoning process. New knowledge and information may displace previous conclusions. That is, while the knowledge and information are increased and solidified as the design process is carried out, they may be invalid if or when the design backtracks.

2.3. Structure of design concept development process

To represent the process of design concept development, two viewpoints can be introduced: a chronological viewpoint that presents the sequence of generating design concepts, and a logical viewpoint that stresses the relationship between a design problem and a design solution. In the former viewpoint, the design process is represented by the transition of design states, each of which is defined as a set of valid design concepts and their related knowledge and information at a certain moment. Using the latter viewpoint, the design process is represented by a network of problems and their corresponding alternative solutions, in each of which the design concepts are different and exclusive, that is, a certain set of alternative design concepts is accepted and the others are not. These two representations are interrelated and complementary.

For explanatory purpose, we quote a fictitious design process in which the design concepts of a new small robot arm are generated and verified as shown in Fig. 1. At the design state 1 in Fig. 1, a designer enumerates sub-functions considered for a robot arm. This can be represented by posing the problem 'what sub-functions does a robot arm have?' (problem-1) and setting its corresponding solution (solution-1). In design state 2, a designer decides solutions for sub-functions, such as 'light sensor is used to detect an object' and 'servo motor is used to move an arm'. This can be represented by posing design problems, namely, 'how should the function 'to detect an object' be realized?'(problem-2), 'how should the function 'to move an arm' be realized?' (problem-3), and so on. Corresponding solutions for those, e.g., 'light sensor' (solution 2-1), are suggested. Prototyping is performed to verify the design concept in design state 3. The results of the analysis show that an object cannot be detected by light sensor, and that this may be because